91602
new 82-10

To: MANAGER
Industrial Marketing/Major Accounts
C27C1

ontario hydro
research division
COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if Reproduced in Whole or in Part

Drying Hardwood Lumber

A.T. Chow

Abstract

A summary of the literature on drying hardwood lumber, particularly using heat pump dehumidification, has been prepared to allow the information to be readily accessible to Ontario Hydro personnel who work with customers in the lumber industry. For that purpose, this summary has been prepared from the perspective of the customer, a dry kiln operator. Included are brief descriptions of drying schedules, precautions needed to minimize drying defects in the lumber, and rules-of-thumb for selecting and estimating the capital cost of the drying equipment.

Introduction

At the request of Mr. J.H. Patterson, (Industrial Marketing), a summary on drying hardwood lumber has been prepared for Ontario Hydro personnel who work with customers in the lumber industry. The purpose of this information is to allow more familiar understanding of the concerns in the lumber drying operation. For this reason, the summary has been prepared from the perspective of the lumber drying customer.

Dried lumber is a high-value-added product, especially when it is of high quality. Lumber damaged during the drying operation can represent substantial lost revenue. Conversely, a lower defect rate represents important savings. Hardwood lumber notably requires special care. Properly dried lumber is stronger, more durable, easier to machine, more readily bonded with adhesive or with chemical treatment, and weighs up to 40% less than green lumber. Dried lumber also has a lower risk of developing stain, decay, and mold. The surface finish is very important in lumber used for manufactured products, such as furniture. Uncontrolled drying in a finished product brings about shrinkages, warping, and undesirable changes in the product's dimensions. The drying operation prevents these defects, provides dimensional stability, and enhances the lumber's properties. The value added to dried lumber reflects its improved quality.

It has been demonstrated that dehumidification kilns can improve lumber quality, and reduce energy consumption over conventional drying methods/3/. This summary includes some of the basic knowledge needed in operating a dehumidification kiln. The aim is not to present all the technical details, but to provide an overview that will induce the right questions to be asked, and indicate the direction for finding the right answers. In addition, Appendix A contains a selection of drying schedules and moisture contents of green lumber. Appendix B contains a glossary of lumber defects and brief descriptions of the possible preventive measures. More specific information can be found in the two publications that are referenced in this summary: *Dry Kiln Operator's Manual*, (1983, U.S. Dept. of Agriculture, Handbook No. 188.), and *Drying Eastern Hardwood Lumber*, (1985, U.S. Dept. of Agriculture, Handbook No. 528.).

job	file	date	report no.
12-178-112	814.35	November 14, 1988	88-228-K

89-04319/

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

The Drying Operation

The average moisture content of green lumber for the various species of hardwood is listed in Table 1 of Appendix A. There are wide variations within the same species, and even within the same tree. The moisture content of lumber is conventionally measured in percent of dry weight (or percent dry basis). A piece of lumber with a dry weight of 100 kilograms and a moisture content of 50% contains 50 kilograms of water. The lumber would weigh 150 kilograms. On average, the moisture content of green hardwood is 82% dry basis. The average final moisture content in kiln dried lumber is 10% dry basis.

It is very difficult to generalize the drying characteristic of different species. The drying rate is related to the wood's permeability to moisture, while the tendency to crack and to check can be attributed to the wood's mechanical properties. In general, the drying rate depends on the temperature, the relative humidity, and the velocity of the surrounding air. The amount of moisture in a piece of wood, after it has been exposed to the surrounding atmosphere for a sufficiently long period of time, is called the equilibrium moisture content (EMC). When the wood is at EMC, it will neither gain nor lose moisture. The EMC depends on the temperature and relative humidity of the surrounding air. Figure 1 shows the typical relationship between the temperature and relative humidity of the air, and the equilibrium moisture content. As illustrated in the figure, the equilibrium moisture content decreases with decreasing relative humidity in the air, and with increasing temperature. The drying operation is essentially keeping the wood in a hot and dry place until the wood dries to the desired final moisture content.

The air velocity is also an important factor. As pictured in Figure 2, higher air velocity will also improve the drying rate. This is particularly critical when removing the initial one third of the moisture in the green lumber. Drying too fast at this stage will create surface check and honeycomb that may not show up until a later stage. High velocity is sometimes used to compensate for high humidity to maintain a reasonable drying rate.

Most of the water in lumber exists as free water in the cell cavities. As a cell loses all of its free water, at about 30% moisture content for all wood, the cell is said to be at the fiber saturation point. Below this point, more heat is needed to remove the bound water in the cell wall, and shrinkage, as well as large changes in physical and mechanical properties, begin to take place. Very fast drying produces a dry surface layer on the lumber, while the interior is still laden with moisture. As a result, the drier surface layer shrinks more than the inside. This creates internal stresses that can split the wood, resulting in surface checks, and end splits. The tendency for developing checks and damages associated with shrinkage is directly proportional to the percentage of shrinkage. Low temperature drying, as in a dehumidification dry kiln, reduces the risk of drying too fast, and the accompanying defects.

There is a maximum drying rate for each species. If the circulating air is too hot, too dry, or too fast, the lumber will develop more cracks, warping, checks, honeycombing and other defects which reduce the value of the dried lumber.

The operator of a dry kiln must decide what is the proper drying rate, or drying conditions, that will produce the best quality of lumber, in the shortest amount of time, at the lowest operating cost. Energy consumption and skilled operator supervision can also be a significant portion of the operating cost. The drying operation can be made

Figure 1

Effects of Temperature and Humidity of
the Surrounding Air on Equilibrium Moisture Content

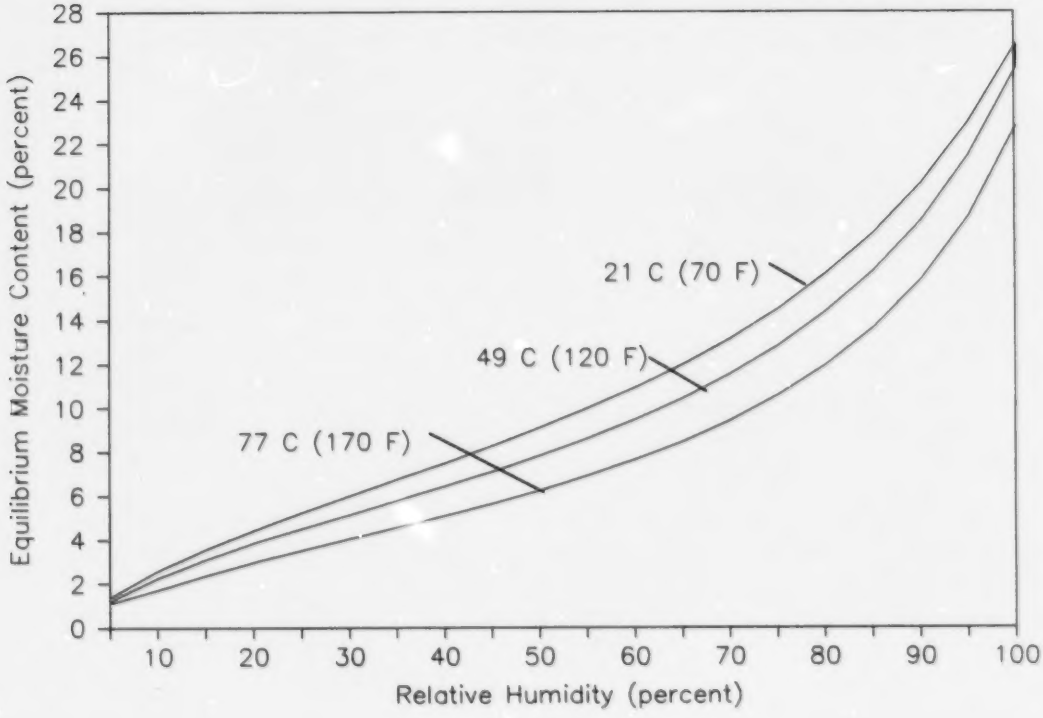
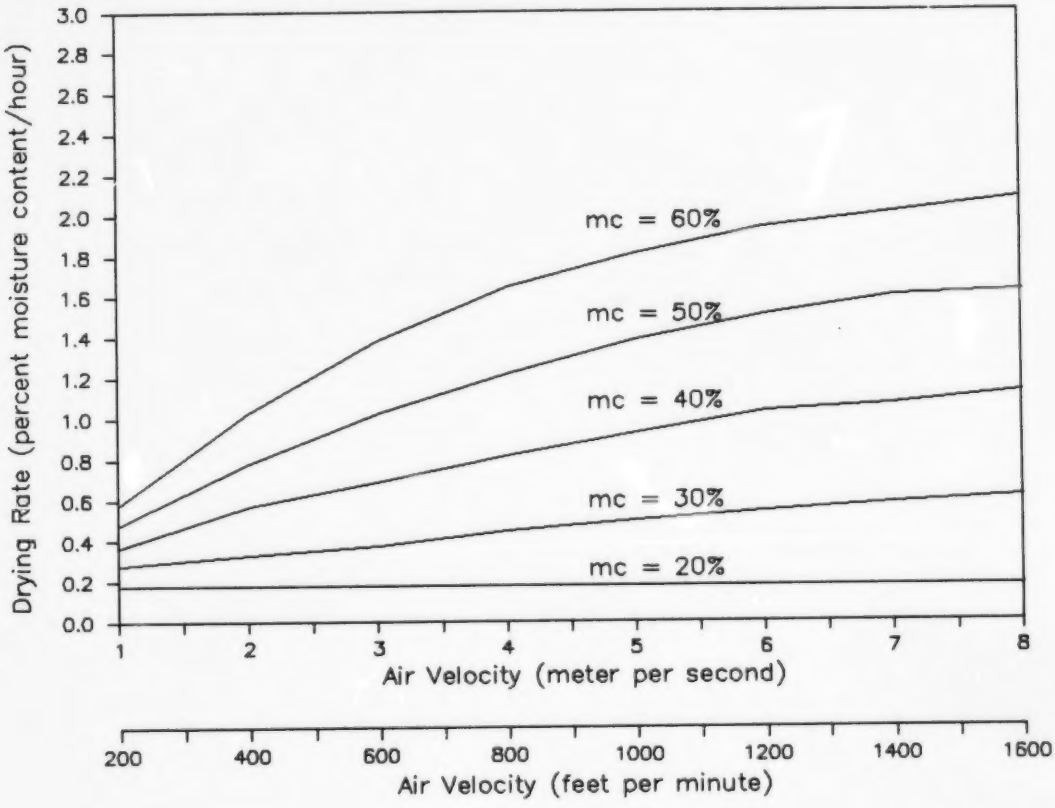


Figure 2

Typical Effect of Air Velocity on the Drying Rate



more profitable by reducing the operating cost, through lower energy consumption, and easier operation. Equally important, profits can be increased by increasing process efficiency, accomplished by reducing the amount of defects in the dried lumber.

The Drying Schedule

The drying schedule is a list of dry-bulb and wet-bulb temperatures recommended for drying a particular species and dimension of lumber. The dry-bulb and the wet-bulb temperatures are respectively the measurements of the temperature and humidity in the kiln. A high wet-bulb temperature means a humid atmosphere. When the wet-bulb temperature is identical to the dry-bulb temperature, the air is said to be saturated with moisture. In some references, only the dry-bulb temperature and the wet-bulb depression are given in the drying schedule. The wet-bulb depression is defined as the difference between the dry-bulb temperature and the wet-bulb temperature. Therefore, a small wet-bulb depression means very humid conditions while a large wet-bulb depression means very dry conditions. In Appendix A, Table 2 presents a selection of typical drying schedules recommended in the Dry Kiln Operator's Manual. They are guidelines that most kiln operators follow. The schedule can be modified slightly for each kiln and each thickness of lumber. If the lumber has been air-dried prior to being loaded into the kiln, the initial portion of the schedule would be modified to account for the lower moisture content. Mixing species in the kiln would also require modified schedules. If the lumber is for construction or other purposes where lower quality of surface finish is acceptable, accelerated schedules with higher temperatures that reduce the drying time can also be used. In applications where the strength of the lumber is desirable, high strength schedules can be used. There are recommended drying schedules for most types of lumber.

The drying schedule can generally be divided into four stages classified according to the moisture content of the lumber. In stage I, the moisture content of the lumber is greater than 2/3 of green moisture content. In stage II, the lumber is between 2/3 of green moisture content and 30% moisture content. In stage III, the moisture content of the lumber is below 30%. In stage IV, the lumber is at the final moisture content and is conditioned to remove casehardening, and to equalize the moisture content in the different pieces of lumber in the pile. The final moisture content is selected according to the average temperature and humidity at the location where the lumber will ultimately be used and how it is treated in the manufacturing process. In North America, the final moisture content ranges from 6% in very dry regions to 15% in more humid climates.

In stage I, the lumber is most susceptible to surface checking. The surface layer of the lumber tends to dry faster than the core. This creates large internal stresses, compressing the core, and stretching the surface. When the stress is greater than the strength of the wood, checks develop. Standard practice at this stage is to dry at low temperatures and high relative humidity. The key is to ensure that the drying rate is less than the recommended maximum rate. The safe drying rates for a few species are listed in Table 3 of Appendix A.

In stage II, as the lumber core begins to dry, the surface tension developed in stage I begins to decrease. If little or no checking has occurred, it would be safe to slowly increase the drying rate by lowering the relative humidity. Temperature should remain low until drying reaches stage III. The strength of wood decreases with increasing temperature, especially at high moisture content. At lower moisture content, temperatures below 70°C (160°F) would not significantly affect the strength of the wood.

In stage III, when the average moisture content of the lumber is less than 30%, it is safe to slowly increase the temperature and lower the humidity to drive out the remaining bound moisture. The internal stresses developed in previous stages are reversed at this stage. The surface is compressed, while the core is in tension. This is called casehardening which causes warping and bending when the lumber is machined. If any deep checks developed in stage I, they may become honeycomb in stage III as tension builds in the core. The average moisture content is allowed to decrease until 1 to 2% below the desired final moisture content, before stage IV begins.

In stage IV, the equilibrium moisture content of the kiln is maintained at the desired final moisture content. The lumber is allowed to equalize with the kiln condition, so that any over-dried lumber can regain the proper moisture content. This also allows the wetter lumber to continue drying closer to the final moisture content. This equalizing step may be omitted if the moisture contents of the sample pieces in different locations in the pile are within the tolerable range. At the very end of the schedule, conditioning with steam is used to release casehardening in the lumber.

The effects of temperature, relative humidity, and velocity on the wood and its drying rate are briefly summarized below. The experienced operator would modify the drying schedule by adjusting combinations of temperature, humidity, and velocity to achieve a safe maximum drying rate.

Temperature:

Drying rate increases with higher temperature.
Warping is more likely with higher temperatures.
Wood strength decreases with increasing temperature.

Relative Humidity:

Drying rate increases with lower relative humidity.
Warping is less likely at lower relative humidity.
Wood is weaker at higher relative humidity.
Checking is more likely at lower relative humidity.
Stain is more likely at very high relative humidity.

Velocity:

Above 40% moisture content, drying rate is higher with higher velocities.
Below 30% moisture content, drying rate is relatively independent of air velocity.
High velocity, especially at the start, increases surface checking and honeycomb.

The Drying Methods

Many different methods have been developed for the drying operation. Heat-and-vent kiln drying is one of the most common. Air drying, using either natural or forced ventilation, is another popular choice. Dehumidification is the most recent method that is becoming widely accepted. This is the method that will be explained in more detail. Heat-and-vent kiln drying is also discussed for comparison.

The air circulation in most kilns are provided by electric fans. The circulating fans are usually reversible to maintain even drying. Since the drying rate is affected by the circulating air velocity, it is worthwhile to use variable speed fans. Variable speed motors can reduce energy consumption in the last two stages of drying, when air velocity is not as important to the drying rate. If a bank of fans are used in the kiln, similar energy savings can be achieved by turning off a portion of the bank, as long as air velocity remains uniform throughout the kiln.

Heat-and-Vent Drying

The heat-and-vent drying process is depicted in Figure 3. Many types of chambers can be used. Figure 4 illustrates a few of the more commonly used configurations.

In the beginning of the drying schedule, and with the vents closed to achieve the high humidity required, the kiln is brought up to temperature by the heating coils. These coils can be heated either electrically, or using a boiler. The boiler can produce either steam or hot water, and can be fired either by fossil fuel or by waste wood. Boilers using waste wood for fuel are usually more expensive and require more maintenance than propane or natural gas boilers. Direct-fired burners, using natural gas, can replace the heating coils, but require special precaution against fire hazards. Selecting the system depends on economic considerations for each individual case.

The vents and the heating elements can be controlled automatically to maintain kiln temperature. Regardless of the controls used, operator supervision is still essential to prevent over drying of the lumber. This is due to the high temperature in the heating elements, and the difficulty in maintaining precise control of the relative humidity. Chart recorders are usually used to keep a record of the dry-bulb and wet-bulb temperatures. At periodic intervals, the operator would examine the kiln conditions and weigh the sample boards to estimate the average moisture content, and calculate the drying rate. The method for properly preparing sample boards is described in detail in the Dry Kiln Operator's Manual. The temperature and humidity in the kiln is adjusted according to the controlling moisture content, which is the average moisture content of the wettest half of the sample boards. When the controlling moisture content has reached the level specified in the drying schedule, the next set of temperature and humidity set points are used for controlling the heaters and the vents. The chart of temperature and humidity, and a record of the other drying information of the load would be useful later when the kiln operator wants to modify the different drying schedules.

At the end of the drying schedule, it is advantageous to introduce steam into the kiln to condition the lumber. The conditioning process produces higher quality surface finishes and reduces casehardening, which is caused by uneven stresses in the lumber. The high temperature and humidity during conditioning releases the internal stress caused by the drying process.

Dehumidification Drying

The dry kiln in a dehumidification system is very similar to a heat-and-vent kiln. Figure 5 illustrates the dehumidification process while Figure 6 shows a few configurations of commonly used dehumidification kilns. Moist air from the kiln is cooled and condensed by the dehumidifier, which recovers the heat from the condensed moisture to re-heat the cool dehumidified air. This hot dry air is then returned to mix with the air in the kiln.

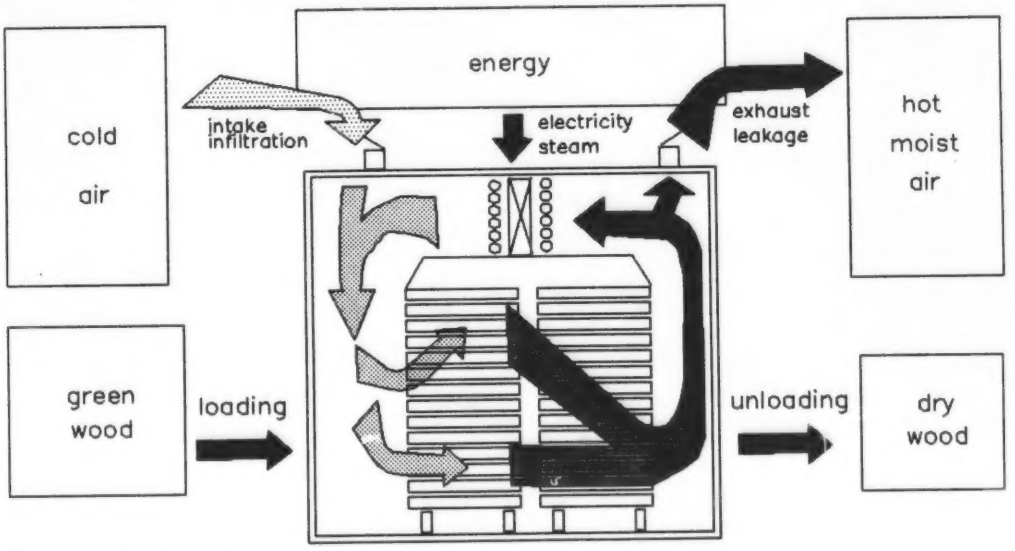
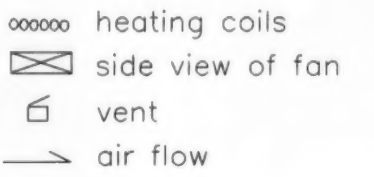
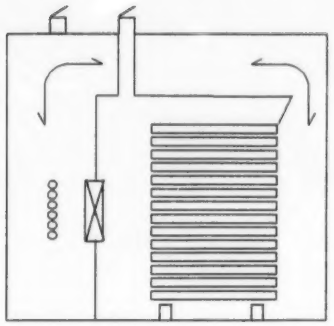


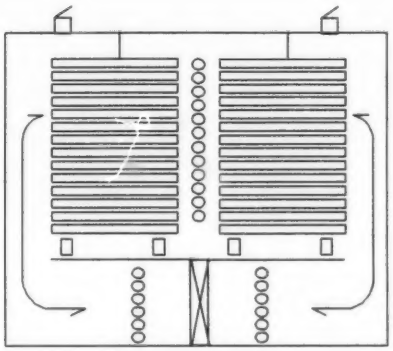
Figure 3: Heat–and–Vent Drying Process

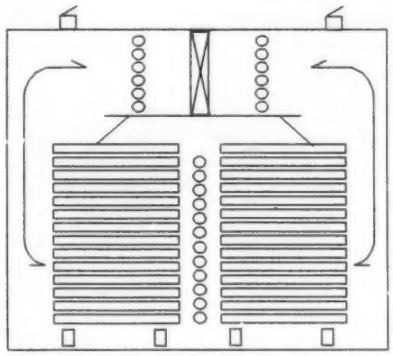
Figure 4:

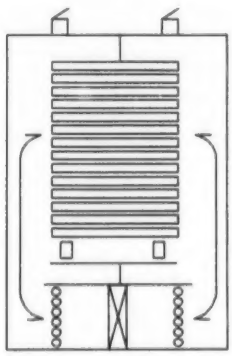
Possible configurations of heaters, fans, and lumber in heat–and–vent kilns

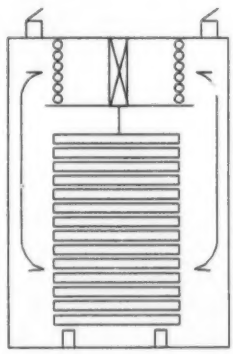












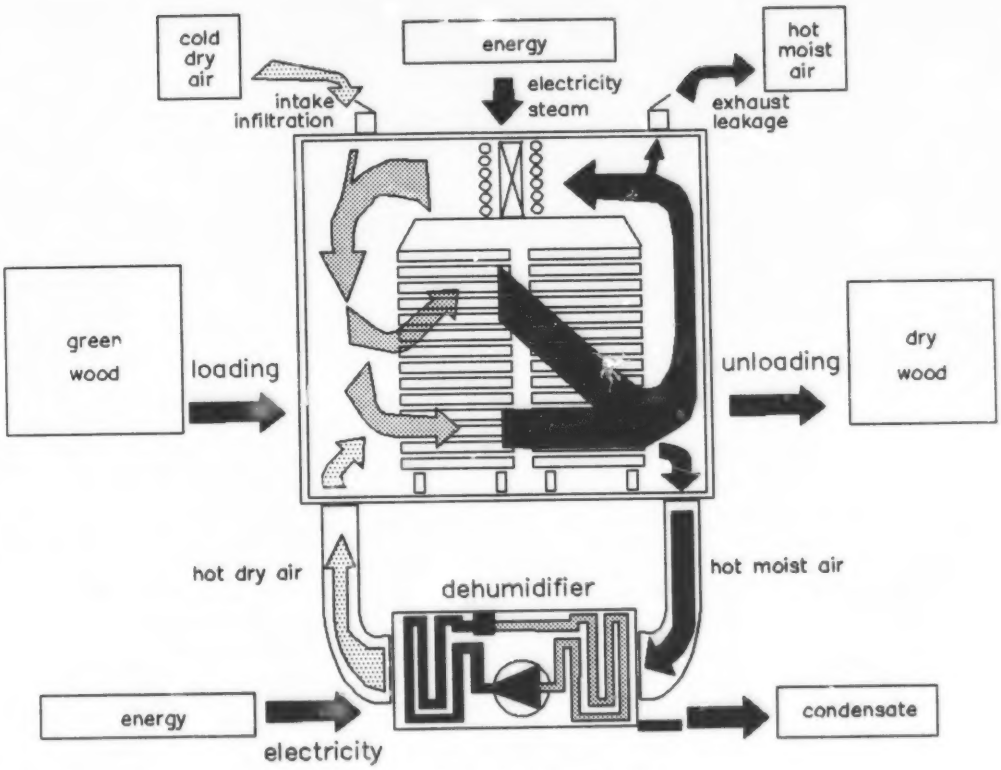
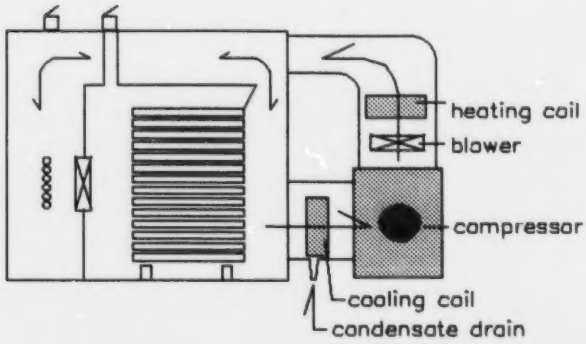


Figure 5: Dehumidification Drying Process

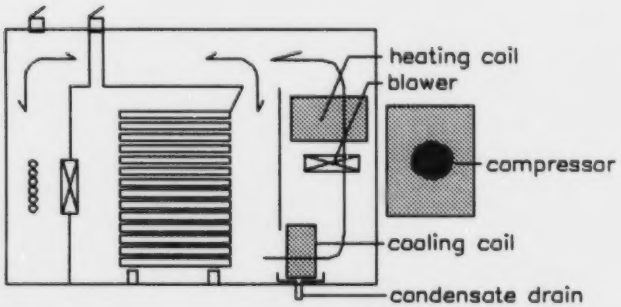
Figure 6:
Possible configurations of
Dehumidification Kilns

Only one configuration is shown to illustrate the location of dehumidifier components. Other configurations can be used as well.

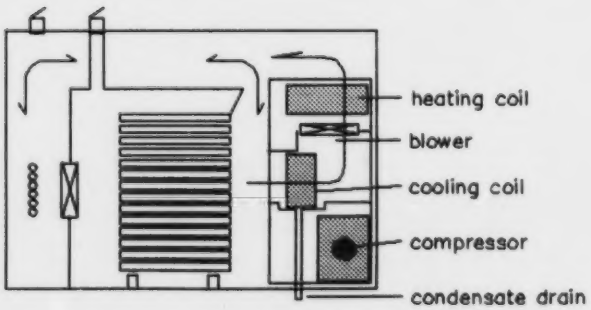
1. external heat exchangers



2. internal heat exchangers



3. internal dehumidifier



The heating coils, either steam or electric, would be used only at the start to heat the kiln to temperature, or to assist the heat pump at the required high temperatures towards the end of some drying schedules. The boiler or resistance heater is therefore much smaller than the one used in the conventional heat-and-vent kiln.

The dehumidifier is capable of maintaining kiln conditions when the kiln is properly constructed with sufficient insulation, and vapour barrier. As in any dry kiln, a high level of leakage would prevent the kiln from achieving the high humidity condition in the beginning of the drying schedule and cause uneven drying in different areas of the kiln. Three to four inches of ordinary foam insulation with a good vapour barrier is, therefore, recommended.

The automatic control for maintaining the proper temperature and humidity is an integral part of the dehumidification system. Since a dehumidifier's capacity to extract moisture from the air is proportional to the relative humidity, it has the desirable feature of being self-limiting. When the relative humidity of the air becomes too dry, less water is extracted by the dehumidifier. The low operating temperature reduces the risk of over-heating or over-drying the lumber. In most cases, daily inspection is sufficient. A small capacity, low pressure boiler is often used to provide the steam used in conditioning the lumber.

Equipment Selection

The drying equipment must be chosen with the kiln's overall efficiency in mind. The components must be sized properly for the given capacity and lumber species. Lumber is commonly measured in thousands of board feet. The board foot refers to a volume of lumber that is one inch thick, 12 inches wide, and 12 inches long, or in other words 144 cubic inches. A thousand board feet means the volume equivalent to a thousand lineal feet of lumber exactly 1 inch thick and 12 inches wide. In other systems of measures: a thousand board feet equals 83.33 cubic feet or 2.360 cubic metres.

1) Dehumidifier:

The sizing criteria for the dehumidifier is a rule of thumb that says: "for each combination of lumber, dehumidifier, and drying schedule, there is a ratio of compressor power per thousand board feet which gives the best drying performance, and capital investment". For most dehumidifiers drying 4/4 red oak, and other slow drying species, it is usually between 0.50 kW to 0.75 kW per thousand board feet. For faster drying species such as the yellow poplar, 1.0 kW to 1.5 kW per thousand board feet can be used. Table 5 in Appendix A is a short list for other species. Dehumidifier manufacturers can usually recommend the best ratio for their own dehumidifiers. In general, the dehumidifier located outside of a kiln will last longer than if it were inside the kiln. It also allows easier access during normal operation and maintenance. When sizing the dehumidifier, it is important not to undersize the compressor because that would reduce the moisture extraction capacity. Reduced capacity means longer drying time, and may cause stains in the lumber from the initial high humidity.

2) Kiln:

The kiln is critical not only for holding the desired volume of lumber, but also for keeping the proper drying conditions. The insulation level has a direct effect on the energy consumption in making up for heat-loss. Three to four inches of foam insulation is generally sufficient. The vapour barrier is vital for maintaining the humidity in the

start of the drying schedule, as well as protecting the integrity of the insulation. The proper length of the lumber pile is essential especially for kilns without reversible fans. If the air is forced through too long a pile, the air temperature and humidity at the exit end would be too cool, and moist for proper drying. The lumber at the entrance side of the pile would dry much faster, resulting in uneven drying, warping, and other defects. The lumber at the exit end would be exposed to air which is too cold and humid. In addition to slower drying, this greatly increases the chance of developing stains in the lumber. The length of the pile should not exceed 7.3 metres (25 feet) for fast drying species such as poplar. The maximum length can be determined for other species by measuring the relative humidity and temperature of the air leaving the pile. The air quality should not deviate significantly from that stated in the drying schedule. Enough space should be provided between the pile and the kiln walls for proper air circulation and access to the sample boards. Baffles that can be lowered from the ceiling and adjusted from the walls are good practices that ensure efficient air circulation. The baffles prevent circulating air from short-circuiting around the pile, and provides more uniform circulation through the lumber.

3) Circulation Fans:

The circulating fans provide the air velocity that improves the drying rate. An approximate rule to determine the volumetric capacity of the fans is available from 1) the cross-sectional area open to air flow, 2) the maximum air velocity in the pile. For example, 50 thousand board feet is equivalent to about 4167 cubic feet. If the sticker used is 50% as thick as the actual lumber, the cross-sectional area open to air flow is 50% of 4167 divided by the length of the pile. A pile 30 feet long gives a cross-sectional area of 70 square feet. If the maximum velocity is 400 feet per minute, the fans would have to provide 400 x 70 or about 28000 CFM. Since the atmosphere in the kiln will be hot, humid, and full of particulates from the lumber the fans must be specified to withstand these conditions.

4) Boiler:

The boiler can be fueled by a number of alternatives. A boiler using propane or natural gas tends to be less expensive and requires less maintenance than a boiler that burns wood waste. The most economical choice depends on individual circumstances. The minimum boiler capacity depends on the capacity of the kiln, the species of lumber, the amount of conditioning in the drying schedule, and the amount of heat loss due to leaks, conduction, and venting. A rough rule of thumb for sizing the boiler in a dehumidification kiln is about 3 kW (10,000 Btu/hr, or 0.3 boiler horsepower) for each thousand board feet capacity. This rule can be modified for different species and conditioning schedules.

Operating Cost of a Dry Kiln

Table 4 in Appendix A shows a breakdown of the operating cost of kiln drying hardwood in the U.S. The operating cost of a drying kiln depends on the type of wood and its drying rate. The cost includes: labour (such as material handling and operator supervision, from 20% to 40% of the total), energy (the cost of running the drying equipment and the heat energy expended in removing the moisture, from 20% to 40% of the total), and miscellaneous taxes, insurance, interests, and maintenance costs. Some of these operating costs, and the cost due to degrade will be discussed in more detail.

1) Material Handling

Loading and unloading the lumber is very labour intensive, and requires specialized equipment. The lumber must be stacked with stickers to provide sufficient ventilation as shown in Figure 7. The stickers are usually 1 to 2 cm (1/2 to 1 in.) thick, and 2 to 5 cm (1 to 2 in.) wide. The spacing between stickers depends on the species. Hardwood species generally use 1 to 1.5 m (3 ft.) wide separation between stickers. Sweetgum and elm, however, require closer spacing at 30 to 50 cm (12 to 18 in.). The closer spacing is also more appropriate for lumber with thickness less than 2.5 cm (1 in.). Properly spaced and aligned stickers help reduce warping and minimize end checks. There are automatic and semiautomatic stacking and unstacking machines available for improving efficiency in placing and in removing the stickers. A package of lumber for a compartment kiln is usually about 1 m (4 ft.) high to allow safe and efficient handling by the fork-lifts. A package of green lumber 3 m long, 1 m wide, and 1 m high (10 ft. x 3 ft. x 3 ft.) can weigh up to 2,500 kg (5,500 lb.). An estimate[1] shows the handling cost to be as much as 1/3 of the total operating cost. Figure 7 shows the bottom half of a package of stacked lumber in relation to the air flow. In general, the cost of material handling is about $30 per thousand board feet.

2) Operator Supervision

The operator is responsible for maintaining the kiln conditions to dry the lumber properly. A number of sample boards are specially prepared to assist in the decision making. Pages 99 to 111 in the Dry Kiln Operators' Manual explain the preparation procedures in more detail. The moisture content of sample boards are examined periodically, and compared with the drying schedule. The temperature and relative humidity in the kiln are adjusted to follow the drying schedule. A typical drying schedule is illustrated in Figure 8. The kiln's dry-bulb and wet-bulb temperatures can be monitored electronically, and controlled to the set points as adjusted by the operator. When the average moisture content of the wettest half of the sample boards is less than the level specified in the drying schedule, the kiln operator would increase the dry-bulb temperature set point, and/or decrease the relative humidity by lowering the wet-bulb temperature set point. This maximizes the drying rate while minimizing the amount of defects.

In a heat-and-vent kiln, the potential for over-drying is so great that frequent operator supervision is required to prevent damaging the lumber. Kiln conditions are monitored and adjusted frequently to ensure proper drying. There is no precise method for doing this, and requires an experienced operator. If a high pressure boiler is used, a certified stationary engineer must be on duty for the duration of the drying schedule. This is not necessary with a low pressure boiler.

In a dehumidification kiln, the operator only needs to inspect the kiln daily. The moisture content of the sample boards would be monitored in the beginning of each day, and the settings for kiln temperature and humidity would be adjusted according to the drying schedule. The water output, refrigerant pressures and temperatures of the dehumidifier would be recorded. This record is used for proper maintenance to be

---

1. Presentation by E.M. Conway, Conway Corp., Grand Rapids, Mich., to Joint Meeting Midwest and Wisconsin-Michigan Wood Seasoning Association, Antigo, Wis., May, 1970.

Figure 7: Stacking Lumber with Stickers

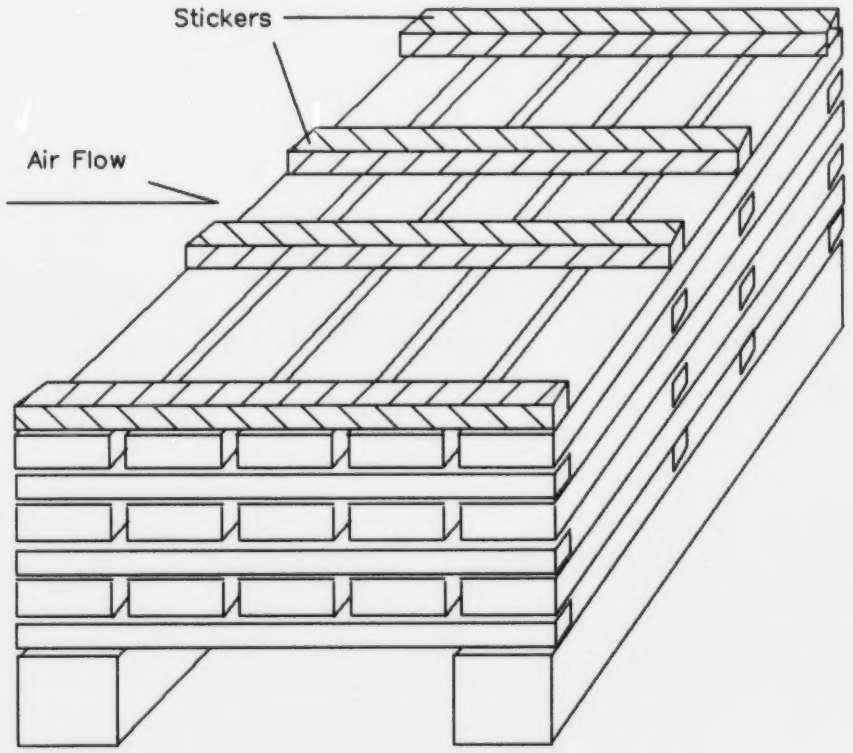
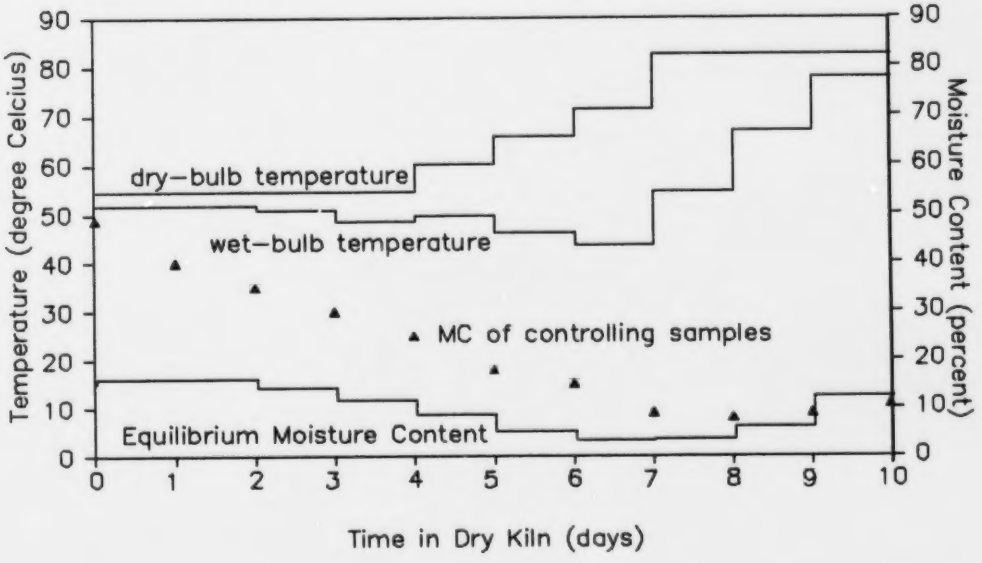


Figure 8
Drying Schedule for 4/4 Sugar Maple



carried out at regular periods, to keep the system operating at peak efficiency. The once-a-day routine can be performed by nearly anyone with a brief training session in the operation.

3) Degrade

In addition to the normal cost of operation, an often overlooked cost is the degraded value due to defects caused by the drying process. The lumber can be damaged when it is dried too fast, or loaded unevenly. Stains can develop if the relative humidity in the kiln is too high during the initial drying period. Various sources[2] indicate that air dried lumber degrade from 0% to 5% in value. Kiln dried lumber would have less than 3%, depending on the method and species in the operation. Drying green lumber directly from the saw mill at low temperature would produce less degrade than kiln drying previously air-dried lumber. Appendix B is a brief description of the types of defects, their causes and remedies. A 1% decrease in degrade for a kiln with 2 million board feet of annual production capacity can represent six to ten thousand dollars additional revenue per year.

4) Energy

Heat energy is required to raise the temperature of the load, evaporate the moisture, and replace heat loss due to exhausted moisture and leakages. Mechanical energy is needed to run the circulation fans in forced-air ventilated kilns. In dehumidifier kilns, electrical energy runs the dehumidifier's compressor, and the heat exchange cabinet's blowers. Due to the dehumidifier's high efficiency, much of the heat used in evaporating the moisture can be recovered. In a moderately efficient dehumidifier kiln, the energy consumed by the fans and auxiliary equipments is approximately the same as that consumed by the dehumidifier. In a heat-and-vent kiln, the heat energy used to evaporate the moisture is the predominant factor. The total amount of energy required depends on the drying rate of the wood. Fast drying wood requires less energy than slower drying species, such as oak. Most dehumidification kilns require from 300 to 600 kW.h to dry one thousand board feet of lumber from green to about 8% moisture content. Starting with a lower moisture content, and drying to a higher moisture content would reduce energy cost. In general, it takes a total of 0.8 kW.h of electricity to remove one kilogram of moisture from the lumber using a dehumidifier. In a heat-and-vent kiln, the ratio is closer to 2 kW.h per kilogram of water.

Capital Cost

Large land surface areas are needed for operating a dry kiln. The lumber is stored before a large batch is stacked and accumulated for the drying operation. The type of storage area can vary widely, from open spaces, covered sheds, enclosed sheds, to heated sheds. The choice depends on the type of drying, the cost of energy, of land, of labour, and the interest on inventory. Open space storage would provide initial air drying at low capital and energy cost. However, open space storage also has a high cost of land

---

2. See references: Cuppett (1966), Hanks and Peirsol (1975), Beall and Spoerke (1973).

area, and waste due to degrade. In northern climates, open air drying is not economical due to the weather conditions most of the year. Sheds of various types provide good opportunities to reduce the initial moisture content of the lumber before kiln drying. Dried lumber must be stored indoors to prevent moisture regain. The best storage for dried lumber is a shed with temperature and humidity control.

The total capital cost of a dry kiln includes the kiln, the low-pressure-steam boiler, and/or the dehumidifier. In operations with annual production greater than 2 million board feet, a large boiler can be used to supply steam for many heat-and-vent kilns. The resulting economy of scale means a lower capital cost. In general, dehumidification kilns usually range from $2.50 to $3.50 per board foot of capacity while heat-and-vent kilns range from $2.00 to $5.00 per board foot.

Conclusions

The economics of a drying operation depend on many factors. The species of the wood has a great influence on the energy consumption, the drying time, and the percentage of degrade. The cost of energy is further affected by the electrical rate, and its relation to the cost of fossil fuel. Even when drying the same species, the starting moisture content, and the final moisture content can have a significant influence on the cost and productivity of the operation.

The advantages of dehumidification kilns are well documented in the literature, and are the driving forces behind the popularity of dehumidifiers in the hardwood drying industry. The low operating temperature in dehumidifiers makes it easier to produce high quality lumber with less degrade. During hot and humid summer months, heat-and-vent kilns often have difficulty achieving the necessary low relative humidity in the latter stages of drying. The efficiency of the dehumidifier on the other hand is independent of the local climate. In addition, the dehumidifier does not exhaust large volumes of vapours, and combustion gases.

Dehumidification kilns in hardwood drying operations consume less energy, are easier to operate, and cost less when compared to heat-and-vent kilns.

Approved by:

for A.F. Baljet
Manager
Electrical Research Department

Submitted by:

A.T. Chow
Engineer
Utilization Section

Reviewed by:

J.M. Bell
Supervising Engineer
Utilization Section

ATC:djb

APPENDIX A - List of Tables

Table 1 - Average Green Moisture Content of Hardwood

Table 2 - Sample Drying Schedules

Table 3 - Recommended Maximum Drying Rates

Table 4 - Operating Cost

Table 5 - Sizing Criteria

Table 1 - Average Green Moisture Content of Hardwood

Species	Moisture Content Heartwood/Sapwood/Mixed		
Alder, red		97	
Apple	81	74	
Ash:			
Black	95		
Green		58	
White	46	44	
Aspen	95	113	
Basswood, American	81	133	
Beech, American	55	72	
Birch:			
Paper	89	72	
Sweet	75	70	
Buckeye, yellow			141
Butternut			104
Cherry, black	58		
Chestnut, American	120		
Chinkapin, golden			134
Cottonwood, black	162	146	
Dogwood, flowering			62
Elm:			
American	95	92	
Cedar	66	61	
Rock	44	57	
Hackberry	61	65	
Hickory:			
Bitternut	80	54	
Mockernut	70	52	
Pignut	71	49	
Red	69	52	
Sand	68	50	
Water	97	62	

Species	Moisture Content Heartwood/Sapwood/Mixed		
Holly, American			82
Hophornbeam, eastern			52
Laurel, California			65
Locust, black			40
Madrone, Pacific			81
Magnolia	80	104	
Maple:			
Silver (soft)	58	97	
Sugar (hard)	65	72	
Oak:			
California black	76	75	
Live			50
Northern red	80	69	
Southern red	83	75	
Southern swamp	79	66	
Water	81	81	
White	64	78	
Willow	82	74	
Osage-orange			31
Persimmon, common			58
Sweetgum	79	137	
Sycamore, American	114	130	
Tanoak			89
Tupelo:			
Black	87	115	
Swamp	101	108	
Water	150	116	
Walnut, black	90	73	
Willow, black			139
Yellow-poplar	83	106	

From Dry Kiln Operator's Manual, USDA Handbook No. 188. P.9.

Table 2 - Sample Hardwood Drying Schedules

All temperatures are given in degrees Fahrenheit, as shown on pages 117 to 145 in Dry Kiln Operator's Manual. Temperatures in degrees Celcius can be calculated from:
temperature in °C = (temperature in °F - 32) x 0.56.

In some references, only the dry-bulb temperature and the wet-bulb depression are given in the drying schedule. The wet-bulb depression is defined as the difference between the dry-bulb temperature and the wet-bulb temperature. Therefore, a small wet-bulb depression means very humid conditions while a large wet-bulb depression means very dry conditions.

Moisture Content at start of step	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
SOUTHERN LOWLAND OAK	4/4, 5/4, 6/4 stock					
>40	100	3	97			
40	100	4	96			
35	100	6	94			
30	110	10	100			
25	120	25	95			
20	130	50	80			
15	150	50	100			
WHITE OAK	4/4, 5/4, 6/4 stock			8/4 stock		
>40	110	4	106	110	3	107
40	110	5	105	110	4	106
35	110	8	102	110	6	104
30	120	14	106	120	10	110
25	130	30	100	130	25	105
20	140	50	90	140	50	90
15	180	50	130	160	50	110
MAHOGANY	4/4, 5/4, 6/4 stock			8/4 stock		
>40	120	7	113	110	5	105
40	120	10	110	110	7	103
35	120	15	105	110	11	99
30	130	25	105	120	19	101
25	140	40	100	130	35	95
20	150	50	100	140	50	90
15	180	50	130	180	50	130
WHITE ASH, CHERRY	4/4, 5/4, 6/4 stock			8/4 stock		
>35	130	7	123	120	5	115
35	130	10	120	120	7	113
30	140	15	125	130	11	119
25	150	25	125	140	19	121
20	160	40	120	150	35	115
15	180	50	130	160	50	110

Table 2 - Sample Hardwood Drying Schedules (continued)

Moisture Content at start of step	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
ASPEN, BASSWOOD	4/4, 5/4, 6/4 stock			8/4 stock		
>60	160	20	140	140	15	125
60	160	30	130	140	20	120
50	160	40	120	140	30	110
40	160	50	110	140	50	90
35	160	50	110	140	50	90
30	170	50	120	150	50	100
25	170	50	120	160	50	110
20	180	50	130	170	50	120
15	180	50	130	180	50	130
BLACK TUPELO	4/4, 5/4, 6/4 stock			8/4 stock		
>60	160	10	150	150	5	145
60	160	14	146	150	5	145
50	160	20	140	150	7	143
40	160	35	125	150	11	139
35	160	50	110	150	19	131
30	170	50	120	160	35	125
25	170	50	120	160	50	110
20	180	50	130	170	50	120
15	180	50	130	180	50	130
MAGNOLIA	4/4, 5/4, 6/4 stock			8/4 stock		
>50	140	7	133	130	5	125
50	140	10	130	130	7	123
40	140	15	125	130	11	119
35	140	25	115	130	19	111
30	150	40	110	140	35	105
25	160	50	110	150	50	100
20	170	50	120	160	50	110
15	180	50	130	180	50	130
BLACK ASH	4/4, 5/4, 6/4 stock			8/4 stock		
>50	130	7	123	120	5	115
50	130	10	120	120	7	113
40	130	15	115	120	11	109
35	130	25	105	120	19	101
30	140	40	100	130	35	95
25	150	50	100	140	50	90
20	160	50	110	150	50	100
15	180	50	130	160	50	110

Table 2 - Sample Hardwood Drying Schedules (continued)

Moisture Content at start of step	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
GREEN ASH	4/4, 5/4, 6/4 stock			8/4 stock		
>35	130	7	123	120	5	115
35	130	10	120	120	7	113
30	140	15	125	130	11	119
25	150	25	125	140	19	121
20	160	40	120	150	35	115
15	180	50	130	160	50	110
RED ALDER	4/4, 5/4, 6/4 stock			8/4 stock		
>50	140	7	133	130	5	125
50	140	10	130	130	7	123
40	140	15	125	130	11	119
35	140	25	115	130	19	111
30	150	40	110	140	35	105
25	160	50	110	150	50	100
20	170	50	120	160	50	110
15	180	50	130	180	50	130
PAPER BIRCH	4/4, 5/4, 6/4 stock			8/4 stock		
>40	140	7	133	130	5	125
40	140	10	130	130	7	123
35	140	15	125	130	11	119
30	150	25	125	140	19	121
25	160	40	120	150	35	115
20	170	50	120	160	50	110
15	180	50	130	180	50	130
SUGAR (HARD) MAPLE	4/4, 5/4, 6/4 stock			8/4 stock		
>40	130	5	125	120	4	116
40	130	7	123	120	5	115
35	130	11	119	120	8	112
30	140	19	121	130	14	116
25	150	35	115	140	30	110
20	160	50	110	150	50	100
15	180	50	130	160	50	110

Table 2 - Sample Hardwood Drying Schedules (continued)

Moisture Content at start of step	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
SILVER (SOFT) MAPLE	4/4, 5/4, 6/4 stock			8/4 stock		
>40	130	7	123	120	5	115
40	130	10	120	120	7	113
35	130	15	115	120	11	109
30	140	25	115	130	19	111
25	150	40	110	140	35	105
20	160	50	110	150	50	100
15	180	50	130	180	50	130
BLACK WALNUT	4/4, 5/4, 6/4 stock			8/4 stock		
>50	120	7	113	110	5	105
50	120	10	110	110	7	103
40	120	15	105	110	11	99
35	120	25	95	110	19	91
30	130	40	90	120	35	85
25	140	50	90	130	50	80
20	150	50	100	140	50	90
15	180	50	130	160	50	110

Table 3 - Maximum Drying Rates

Species	Maximum Rate of Moisture Content Loss Per Day*	
	4/4 stock	8/4 stock
Beech	4.5	1.8
Birch, yellow	6.1	2.4
Cherry	5.8	2.3
Elm, American	10.4	4.1
Maple, soft (sap)	13.8	5.5
Maple, hard	6.5	2.6
Oak, red upland	3.8	1.5
Oak, white upland	2.5	1.0
Oak, southern	1.0 to 3.0	-
Sweetgum (red gum)	5.3	2.1
Tupelo (black gum)	10.9	4.3
Walnut	8.2	3.3

* Rate based on losses from properly prepared kiln samples.

From *How to Manage a Drying Operation with Zero Defects*, by Dr. E.M. Wengert, Furniture Design and Manufacture, November, 1980.

Table 4 - Kiln-Drying Cost (1976 US $ per thousand board feet) (percent of total cost)*

item	drying time: 5 - 7 days		drying time: 10 - 15 days	
Equipment depreciation	1.40	3%	2.80	5%
Insurance	0.80	2%	0.80	1%
Maintenance	1.95	5%	1.95	4%
Supplies	0.70	2%	0.70	1%
Sticker replacement	0.50	1%	0.50	1%
Steam and electricity	8.40	20%	16.80	31%
Handling Cost[1]	18.45	44%	18.45	35%
Labour	7.95	19%	7.95	15%
Land and building	1.30	3%	2.00	4%
Interest on inventory (8%, including 10 days of storage)	0.80	2%	1.50	3%
Total	42.25		53.45	

* From Page 77 of *Drying Eastern Hardwood Lumber*, 1985. U.S. Dept of Agriculture, Handbook No. 528. McMillen, J.M. and Wengert, E.M. Presented by E.M. Conway, Conway Corp, Grand Rapids, Michigan, to Joint Meeting Midwest and Wisconsin-Michigan Wood Seasoning Association, Antigo, Wisconsin, May, 1970. Updated by E.M. Wengert, 1976.

[1] Handling cost can be further broken down:

	(1976 US $ per thousand board feet)	(% of total handling)
Labour	14.10	76%
Equipment depreciation	1.50	8%
equipment maintenance	1.25	7%
land and building	0.70	4%
insurance	0.40	2%
miscellaneous	0.50	3%
TOTAL	18.45	

Table 5 - Sizing Criteria (dehumidifier compressor power per thousand board feet kiln capacity)

A. From Dr. E.M. Wengert's article: *Drying at the Saw Mill with Dehumidifiers*, March 1980, Northern Logger and Timber Processor.

Species	horsepower	kilowatt
4/4 thickness		
slow drying species		
oak, beech	0.5 to 0.7	0.3 to 0.5
normal drying species		
maple, birch, elm, ash	0.9 to 1.2	0.7 to 1.0
fast drying species		
aspen, pine	1.0 to 2.0	0.8 to 1.6

8/4 thickness
Use 50% to 75% of values for 4/4 thickness.

B. Another method for sizing the appropriate unit is based on the maximum drying rate given in Table 3. The maximum safe drying rate and the calculated weight of lumber per thousand board feet are used to estimate the moisture removal capacity, and the compressor size. This is only approximate because it is based on the maximum drying rate instead of the actual drying rate.

4/4 thickness	hp/MBF green	kW/MBF green	drying rate %mc/day
beech	0.9	0.7	4.5%
yellow birch	1.1	0.8	6.1%
cherry	1.3	1.0	5.8%
american elm	0.9	0.7	10.4%
soft maple	1.9	1.4	13.8%
hard maple	1.2	0.9	6.5%
red upland oak	0.7	0.5	3.8%
white upland oak	0.5	0.4	2.5%
southern oak	0.3	0.2	2.0%
sweetgum red gum	0.8	0.6	5.3%
tupelo black gum	1.6	1.2	10.9%
walnut	1.3	1.0	8.2%

8/4 thickness
Use 40% of values for 4/4 thickness.

APPENDIX B - Defects: their causes and remedies

The following sections are condensed from pages 147 to 153 of the Dry Kiln Operator's Manual.

A. Defects Associated with Shrinkage

Shrinkage in wood begins when moisture content drops below the fiber saturation point (about 30%). Tangential shrinkage occurs parallel to the annual growth rings; radial shrinkage is across the rings. Depending on the species, the radial shrinkage can be up to 7% at 0% moisture content. The longitudinal shrinkage along the grain is normally very small (about 0.2%). Tangential shrinkage is usually 1.5 to 2 times greater than radial shrinkage.

1. **Surface checks** usually occur on the flat-sawn faces of the lumber, and occasionally on the edges of lumber thicker than 6/4. The checks usually develop early in the drying schedule, and sometimes close up later in the drying process. Some applications of the lumber may not be affected by closed checks. In other products requiring high quality finishes such as cabinets and bookcases, closed checks are undesirable because they may open again with fluctuating atmospheric conditions. Surface checks are caused by dry surfaces of the lumber as a result of excessively low relative humidity. Lumber with surface checks from air drying in the early stages should not be allowed to regain moisture. Re-wetting often causes checks to become longer, deeper, and wider. Re-wetting can be due to water sprayed on the lumber, rain, condensation from the humid atmosphere on cold lumber, and exposure to excessively high relative humidity either before or after drying. To prevent surface checks from developing during transport and in storage, the lumber should be stored under-cover and not be exposed to high winds. Green lumber should be kiln-dried as soon as possible, at the appropriate conditions.

2. **End checks**, are similar to surface checks except they occur on end-grain surfaces. The likelihood to end check increases with the width and the thickness of the lumber. In addition to the precautions for preventing surface checks, end coatings should be applied to freshly cut, unchecked ends of green lumber. The end coating reduces the amount of evaporation from the ends, and reduces the likelihood of excessive drying.

3. **End splits** are usually extension of end-checks. In addition to the precautions to reduce end checks, aligning the stickers at the extreme ends of the board can often reduce the likelihood of developing end splits.

4. **Collapse** develops early in the drying process. In stage I drying, the surface layer of the wood shrinks more than the interior. This creates compression in the interior of the wood. If the compressive stress is greater than the wood's compressive strength, the wood cells flatten or collapse. Collapse generally is not visible until later in the process. Maintaining low temperature in the initial drying period would help to reduce collapse. Special drying schedules are recommended for woods susceptible to this defect.

5. **Honeycomb** is caused by tensile failure inside the lumber. It is produced when excessively high temperatures are maintained for too long, while the cell cavities contain free water. Deep checks that have closed on the surface but remain open below are also called honeycomb. This defect can be minimized by avoiding excessively high temperatures until all the free water has been evaporated. This is usually at average moisture content below 30%.

6. **Ring failure** is caused by tensile failure found parallel to the annual rings. It can be due to extension of a failure in the end grain in the initial stages, or casehardening in the later stages. End coating, high initial relative humidity, and low dry-bulb temperature can help reduce ring failure.

7. **Boxed-heart split** is due to the severe stress caused by the difference between tangential and radial shrinkage of the wood surrounding the pith. The split starts in the initial stages and becomes progressively worse as the shrinkage increases. Very little can be done to prevent this defect.

8. **Warping** is the distortion caused by the differences in shrinkage along the three axis of the wood: radial, tangential, longitudinal. Warping is further intensified by irregular and distorted grain in the wood. Most warping can be controlled by using proper piling procedures.

9. **Checked knots** are produced by the differences in radial and tangential shrinkage in the annual rings within the knots. Although they are almost impossible to prevent, drying at higher relative humidity and to a higher moisture content can help control this defect.

10. **Loose knots** are the results of encased knots loosening during drying. An encased knot shrinks considerably in both length and width, while the lumber shrinks only slightly in length. Very little can be done to prevent this except to dry to a higher moisture content.

11. **Casehardening** is the inevitable result of differing shrinkage during the drying process. The surface of the wood and the inside of the wood dries at different speeds, with different amount of shrinkage, resulting in tensile and compressive stresses. This is undesirable for lumber that is to be machined. Conditioning in the end of the drying schedule effectively relieves casehardening. Page 163 of The Dry Kiln Operator's Manual gives more detail of the conditioning process.

B. Defects Associated with Fungi and Bacteria

Three types of defects can be attributed to fungi: sap stain, decay, and mold. Sap stain (or blue stain) is caused by a fungi that develop under certain conditions. The conditions most suitable for rapid growth is a temperature between 24 and 29 °C (75 and 85 °F) in wood at moisture content greater than 20%. Rapid drying of green lumber and chemical treatment can reduce and often eliminate sap stain from developing.

Bacteria infected wood generally dries slower, is weaker, smells rancid, and discolors. The infection is usually confined to the part of the tree which is less than 2.5 meters (8 feet) from the ground. It is caused by anaerobic bacteria in the soil on wet sites, and on older trees. Problems associated with bacteria infected lumber include: returning smell when dried lumber is exposed to high humidity or water, splintering and shattering

during machining, honeycomb, and stains. If infected lumber can be used, dry slowly to reduce checks, and other defects caused by shrinkages. For example, use schedules for 8/4 lumber on 4/4 lumber.

C. **Defects Associated with Chemicals**

Many naturally occurring chemicals and extractives in the wood undergo changes during the drying process. These changes may cause discolorations or chemical stains.

1. **Pinking** in hickory does not affect the strength of the wood, but is sometimes considered a defect. This pink coloring can be prevented to a large extent by using a special drying schedule found on page 127 of the Dry Kiln Operator's Manual.

2. **Sticker marking** is a narrow, dark streak on the surface of the wood, located at the edges of the stickers. These markings can be minimized by using dry, narrow stickers, or grooved stickers to reduce the contact area. Starting the drying of green lumber as soon as possible will also help.

References and Bibliography

1. Rasmussen, E.F.
   Drying Kiln Operator Manual, 1983. U.S. Dept of Agriculture, Handbook No. 188.

2. McMillen, J.M. and Wengert, E.M.
   Drying Eastern Hardwood Lumber, 1985. U.S. Dept of Agriculture, Handbook No. 528.

3. Ciz, J.
   Research Report: 84-59-K: Dehumidification Heat Pump Wood Dryer - Performance Evaluation, 1984.

4. E.M. Wengert.
   Dehumidification Kilns Operation course notes, 1987.

5. E.M. Wengert.
   Dehumidification Dry Kilns vs. Standard Steam Kilns, June 1987, Northern Logger and Timber Processor.

6. E.M. Wengert.
   Drying at the Saw Mill with Dehumidifiers, March 1980, Northern Logger and Timber Processor.

7. Strack, J.T. and Howell, B.
   Research Report: 84-33-K: Survey of Wood Drying Kilns in the Province of Ontario, 1984.

8. Beall, F.C. and G.R. Spoerke.
   Degrade of Oak Lumber as Influenced by Drying, 1973. Forest Product Journal. 23(11):25-30.

9. Cuppett, D.G.
   How to Determine Seasoning Degrade Losses in Sawmill Lumber-yards, 1965. USDA Forest Service Research Note NE-32. Northeast For. Exp. Stn., Upper Darby, Pa.

10. Cuppett, D. G. and Craft, E.P.
    Low-Temperature Drying of 4/4 Appalachian Red Oak, 1971. Forest Product Journal 21(1):34-38.